Geology of the Socorro Mine-White Marble Mine Area, Western Harquahala Mountains, West-central Arizona

Stephen M. Richard

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## GEOLOGY

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Introduction

This map documents the complex deformation in a northeast-trending belt of steeply dipping Paleozoic strata in the footwall of the Harquahala thrust in the Socorro Mine-White Marble mine area of the western Harquahala Mountains. The remarkable deformation in the lithologically heterogeneous Paleozoic section records progressively increasing strain northeastward towards the Harquahala Thrust. These rocks form the structural setting for gold mineralization in the Socorro Mine area, a gypsum mine in the Kaibab Formation east of the Socorro Mine, and for decorative stone quarried from Martin Formation in the White Marble Mine area. Previous maps of this area have been published by Varga [1977] and Keith et al. [1982].

Geologic Setting

Paleozoic rocks in the western Harquahala Mountains lie at the eastern end of the Cretaceous Maria Fold and Thrust Belt [Reynolds and others, 1986], a S- to SE-vergent belt of folding, thrusting and metamorphism that bounds the east-trending McCoy Basin [Harding and Coney, 1985] on the north. Within the McCoy basin Jurassic(?) and Cretaceous sedimentary rocks are up to 7 km thick. The McCoy basin and Maria fold and thrust belt define a transverse sedimentary rocks zone that lies athwart the north to northeast trend of both the Paleozoic Cordilleran miogeocline and Cretaceous fold and thrust belt.

In west-central Arizona, Paleozoic rocks are preserved in the footwall of Mesozoic thrust fault systems. In the Plomosa [Miller, 1970; Richard and Spencer, 1994, Richard et al., 1993], Granite Wash [Laubach, 1986; Laubach et al., 1989; Reynolds et al., 1991] and Little Harquahala [Richard, 1983; Spencer et al., 1985] Mountains, Paleozoic strata from steeply southeast-dipping, northeast trending strike belts. In the Granite Wash Mountains, Laubach et al. [1989] interpreted the geologic history to comprise a top-to-the-southeast large-scale folding event, followed by top-to-the-southwest thrusting of Proterozoic crystalline rocks on top of the folded Paleozoic and Mesozoic strata. A similar interpretation has been applied to deformation in Paleozoic strata within the White Marble Mine-Socorro Mine area [e.g. Reynolds et al., 1986]. In the course of this study, the existence of a southeast-facing recumbent fold that predates the Harquahala thrust could not be conclusively demonstrated.

Mesozoic structures in the Harquahala Mountains are exposed as a result of uplift and erosion during Early Tertiary time and tectonic denudation in Miocene time [Richard et al., 1990a]. Low-angle normal faults of Tertiary or probable Tertiary age are exposed along the southeast side of the map area. The youngest structures recognized in the map area are a series of northwest-trending high-angle faults. These faults have complex displacement histories.

Harquahala Thrust

The Harquahala thrust superposes Proterozoic igneous and metamorphic rocks on top of Proterozoic granitoids and overlying Paleozoic and Mesozoic sedimentary rocks [Richard, 1988]. The thrust dips gently south, such that the central part of the Harquahala Mountains is a klippe of the upper plate. Lower plate rocks
Figure 1. Map showing location of study area within state of Arizona, and place names referred to in text.
appear again on the south side of the range due to folding of the thrust or to later faulting (Figure 2). Reconstruction of Tertiary deformation implies that the Harquahala thrust system is a zone of right-oblique thrusting [Richard et al., 1990a]. The age of the Harquahala thrust is bracketed between ~160 Ma and 77 Ma. Minimum slip on the thrust is 16 km, based on overlap of unlike rock types and estimates of shear strain in underlying Paleozoic rocks [Richard, 1988].
Geometry

The thrust is a simple, discrete, planar ductile shear zone along the north side of the Harquahala Mountains, where its footwall is relatively homogeneous Proterozoic biotite granite (unit Yh). High strain zones associated with the thrust contain L-S tectonites with foliation oriented sub-parallel to the adjacent fault, and stretching lineations that trend 000°. A tectonite zone 5-10 m thick is preserved in both the footwall and hanging wall of the Harquahala thrust zone in the area northeast of the White Marble Mine. In thin section, quartz and feldspar porphyroclasts in tectonites along the thrust are flattened in the foliation. Quartz occurs as granoblastic aggregates. Potassium feldspar typically is fractured, with quartz and new potassium feldspar filling the fractures; some subgrains are developed. Plagioclase is ubiquitously recrystallized to a fine-grained aggregate of albite or oligoclase and quartz that forms a major component of the matrix, along with muscovite, biotite, and recrystallized tails of potassium feldspar porphyroclasts. Muscovite occurs as a mat of very fine-grained crystals defining an anastomosing schistosity. Fine-grained, green to brownish-green biotite is disseminated in the muscovite. Matrix grain size averages approximately 5 microns. Lineation in these tectonites is weakly developed, but where visible has a streaky character defined by elongate aggregates of feldspar and biotite. Quartz grains are not greatly elongated.

In the White Marble Mine area, the Harquahala thrust crosses southward across the upturned base of the Paleozoic section. Deformation associated with the Harquahala thrust affects large volumes of rock, producing gently dipping shear zones and transposed bedding in Paleozoic and Mesozoic strata. Paleozoic and Mesozoic strata below the thrust were tilted steeply to the southeast before emplacement of the Harquahala thrust, but major overturning of the Paleozoic section is due to shearing below the Harquahala thrust.

Slip on Harquahala thrust system

Overlap of dissimilar rock units indicates that the upper plate of the Harquahala thrust has been transported a minimum of 14 km to the south. Contacts in the Proterozoic gneisses are not greatly offset to the east or west across the SE-dipping shear zones in the Arrastre Gulch area, indicating that slip on these must be mostly N-S. An estimate of the minimum magnitude of shear strain (g) required to produce the tectonic thickness of the transposed section in the lowest plate of the main Arrastre Gulch window can be made by assuming that the dip of the section was vertical before deformation, that the deformation was simple shear, and that the stratigraphic thickness of the Kaibab and Coconino formations was the same as in the relatively undeformed section in the Little Harquahala Mountains. The thickness of deformed Coconino Quartzite yields a g value of 5.1. Because the thickness of the Kaibab is more uncertain, the g value lies between 3.9 and 8.8. The thickness of the shear zone is estimated to lie between 520 and 630 m, assuming that the uniform foliation in the central part of the window is parallel to the boundary of the shear zone, and measuring the thickness of deformed Supai, Coconino, Kaibab formations and basal Mesozoic sediments perpendicular to this surface. The minimum displacement across the section so calculated is between 2 and 5.5 km, with a best guess value of ~3 km.

Age of thrust

The precise age of the Harquahala thrust is uncertain. It is bracketed by the 160 Ma Black Rock volcanics [Reynolds and others, 1987] that are deformed in the lower plate of the Hercules thrust of the western
Harquahala Mountains and by the 77±7 Ma age of the Brown’s Canyon granite [Isachsen et al., 1999], which cross-cuts the thrust.

**Structural Geology**

**Structural style in Paleozoic units**

The Paleozoic section can be divided into several mechanical units, with contrasting responses to deformation. There seems to be little mechanical contrast between the medium bedded, coarse-grained feldspathic part of the lower Bolsa Quartzite and underlying granite. Detachment zones tend to develop in thin-bedded upper Bolsa Quartzite, leading to discordance between the base and upper contact of the formation. The contact between the Bolsa Quartzite and underlying granitoids is generally a steeply dipping to vertical non-conformity from the southwest end of the map area to near the Silver Queen Fault. Northeast of there, the Bolsa is generally overturned, but locally is upright with the basal non-conformity preserved. Thin-bedded, fine-grained Abrigo Formation also acts as a detachment zone, and its thickness is widely variable.

Carbonate rocks of the Martin Formation and Redwall Limestone form the second mechanical unit. Dolomite of the Martin Formation resists folding and transposition in a manner comparable to the Bolsa Quartzite, but complex intraformational wedging and buckling disrupts continuity of beds. Thick-bedded to massive carbonate units of the Redwall Limestone are generally concordant with bedding in Martin Formation southwest of the Hidden Treasure Fault. Pure limestone units at the base and top of the Redwall exhibit progressively more plastic deformation from there northeast, and massive dolomite in the middle of the Redwall Formation detaches and breaks into large boudins immersed in a matrix of lower Redwall limestone, upper Redwall limestone and basal Supai Formation in the central part of the map area. Domains of upright and overturned bedding are present throughout the map area wherever bedding and stratigraphic sequence can be identified in Redwall Limestone and Martin Formation. The variability is attributed to unmapped small scale intraformational faulting. These carbonate rocks are recrystallized and transposed in the vicinity of the Harquahala thrust.

Above the limestone at the top of the Redwall, the interbedded, limestone-rich Supai Formation deforms very heterogeneously. At the southwest end of the outcrop belt, Supai Formation is relatively coherent and forms prominently ribbed outcrops, with bedding delineated by thick sandstone beds with black desert varnish alternating with non-resistant or weakly varnished calcareous units. From about Socorro Peak northeast, bedding in Supai Formation is variable except in small (10's of m) domains, and Supai outcrops are dominated by tectonic fabrics related to plastic deformation of the unit. Quartzite and calcareous sandstone beds remain relatively rigid and break up into 5 - 15 m size blocks, which rotate to parallel shear zone boundaries. Shale and limestone beds flow around these rotating blocks. Within transition zones to high strain, domains of transposed and non-transposed bedding are irregularly distributed. Steeply-dipping bedding preserved in low-strain zones is rotated into the plane of gently dipping transposed bedding in more highly strained outcrops only 20-30 m away. Such transition zones are well exposed in the basin on the northeast side of Hidden Treasure Canyon. In high strain zones this process produces a uniform, gently dipping tectonic foliation defined by transposed bedding. Northeast of Silver Queen Canyon, Supai Formation is entirely transposed.
Coconino Quartzite is characterized by intense fracturing throughout the map area. Some plastic flow is apparent in the limbs of folds. Plastic deformation and transposition of bedding to a gentle dip is more pervasive to the northeast, but domains of steeply dipping bedding are present throughout the unit. Bedding in the Coconino Quartzite between Silver Queen and Hidden Treasure canyons varying erratically on a scale of 10's of meters. The extremely wide outcrop belt of Coconino in this fault block, in combination with the generally moderate to steep bedding observed, requires the presence of a distributed system of faults. The quartzite is interpreted to have flowed by large-scale cataclasis that has spread the quartzite like chunky peanut butter across the top of underlying transposed Supai Formation. In the Hidden Treasure Canyon area, a steep contact between Supai Formation and Coconino Quartzite is generally concordant to bedding in the quartzite, but the contact is sheared and is shown as a fault. This fault is interpreted as a strain discontinuity between two rock bodies (Supai Formation and Coconino Quartzite) with radically different mechanical properties.

The lower, dolomitic part of the Kaibab Formation resists transposition and is broken into blocks preserving depositional contacts with underlying Coconino Quartzite. The middle and upper limestone units of the Kaibab are easily transposed and appear to flow quite readily. Kaibab Formation is generally upright and steeply southeast-dipping as far northeast as the gypsum mine near Hidden Treasure Canyon, where the formation becomes overturned in the fold structure described below. Gypsum in the upper Kaibab appears to be localized along a boundary between overturned but non-transposed Kaibab Formation above, and transposed limestone tectonites derived from Kaibab Formation below. The Kaibab is once again upright and non-transposed northeast of Hidden Treasure Canyon, but only the lower part of the formation is preserved beneath a Tertiary low-angle normal fault. Along strike, a similar pattern of northeastward change in strike and overturning is repeated, but the structure is within the basal Kaibab and Coconino Quartzite, and is overprinted by a younger shear zone along the range boundary (see discussion under Folds).

Folds

The gentle, recumbent, S-facing syncline-anticline pair in the Kaibab Limestone is prominently displayed in cliffs northeast of the Socorro Mine [Varga, 1977] (see cross sections B-B' and BB-BB', section locations shown in Figure 3). Varga [1977] interpreted folds in Kaibab Limestone and Supai Formation southeast of the Hidden Treasure Fault (Figure 4) as cascade folds related to top-to-the-southeast gravity gliding. Lineations on minor slides within this fold trend north, parallel to lineations associated with the Harquahala thrust. No fabrics were observed that require the existence of an older southeast-vergent recumbent fold structure. The fold is spatially associated with Fault 6 (Figure 4), and the geometry of the fold suggests that it might be related to shearing beneath the Harquahala Thrust or associated with Fault 6.

The transition from mostly upright to mostly overturned section is not related to the fold structure described above. Such transitions occur along strike on the east side of Socorro Peak, and again northeast of the Hidden Treasure fault (Fig. 5). The best exposed transition from upright to overturned is in Kaibab Formation along the range front southeast of Hidden Treasure canyon. In this area, the transition occurs across a zone that is oblique to the strike of bedding, trending about N035°E, with a steep dip to the southeast. The geometry is best described as a twist. The zone of twisting projects towards the Hidden Treasure fault (Fault 17, Fig. 4), but loses clear definition at the base of the Kaibab Formation. Coconino Quartzite and Supai Formation are variably upright and overturned and structure within these units does not fit the twisting geometry observed in
the Kaibab. Structure in the lower part of the Paleozoic section northeast of Socorro Peak is bizarre. It is disposed in an along-strike ‘twist’ that is geometrically similar to and along strike with, the overturning zone in the Kaibab. The zone in the lower Paleozoic rocks is broken into blocks along the Hidden Treasure fault, and deformation related to the Hidden Treasure fault is interpreted to be superposed on that related to the twisting.

Along strike to the northeast is another transition from mostly upright section to overturned section. Northeast of the Hidden Treasure fault, the Paleozoic section is once again mostly upright, except for the Redwall
Fig. 4. Shows major faults in map area, numbered for identification in text.

and lower Supai. (This part of the stratigraphic section is overturned in otherwise upright sections near the Socorro Mine, and a similar pattern of overturning is observed in the area of the Needle in the Little Harquahala Mountains [Spencer et al., 1985; Richard, 1983].) Once again, northeast-trending, moderately to steeply dipping upright Bolsa Quartzite and Kaibab Formations can be traced into northwest-trending, northeast-dipping overturned strata. The low-angle fault that contains Coconino Quartzite and Supai Formation in its hanging wall (Fault 18+20+21) overlaps this zone of disruption in bedding. The low-angle fault is thus younger or forms a detachment zone below which the twisting deformation developed.
Fig. 5. Structural domain in the map area, showing zones of twisting along strike from upright to overturned, and domain of transposed bedding.

A third geometrically similar zone of twisting is observed at the northeast end of the Paleozoic strike belt in the northeastern part of the map area. Bolsa Quartzite beneath the Harquahala thrust swings to a NW strike and is strongly overturned as it disappears beneath the thrust. This twisting zone may be related to the two zones described above, or may be directly related to shearing in the Harquahala thrust zone. There are insufficient data to rule out either hypothesis.

Rocks in the hanging wall of the Hat Mountain fault are disposed in a dismembered fold (Figure 6). The deformation highlights the contrast in deformation styles between the Bolsa and Martin formations and overlying...
units. Gently to steeply dipping bedding in the Bolsa and Martin formations is preserved in a series of fault slivers, each of which is translated southward relative to the one below. When the slivers of Bolsa Quartzite are reconstructed, they form the limbs of a south-dipping homocline with a monoclinal warp. The Redwall and Supai Formations have been highly deformed and transposed into sub-horizontal sheets and isoclinal folds. Note also that the geometry of the fault slivers suggests a southward convergence of listric faults.

Redwall, Supai and Coconino formations are involved in at least two recumbent, tight to isoclinal folds in the southeastern part of the map area (Figure 7; cross sections F-F’, G-G’, and H-H’). The fold labeled Fold #1 on Figure 7 is spatially associated with Fault #22 (Fig. 4). This fold is unusual in that it is northwest-facing, with Coconino Quartzite in the core. The fold is sandwiched between a shear zone interpreted to connect with Fault 21, and that superposes Coconino Quartzite on overturned, transposed Supai Formation (Cross section F-F’), and Fault 22. Very little of the overturned upper limb is present beneath Fault 22. The northwestward younging of lower Paleozoic strata in the hanging wall of Fault 22 suggests that it is a shear zone representing the overturned limb of Fold #1. Fold #1 disappears to the northeast in a body of highly strained, transposed Supai Formation. Fold #2 lies on the approximate projection of the hinge surface of Fold #1, but it is a tight isoclinal fold with Redwall Limestone in the core. The dotted fault shown on Figure 7 represents a possible pre-metamorphic fault within the Supai Formation that put the Redwall and Coconino close to each other. Although the southward-closing antiformal geometry of this fold is constant across this boundary, the stratigraphic facing direction reverses, presenting another enigmatic relationship.

Transposition

As deformation becomes more intense to the northeast, moderately to steeply dipping strata were sheared to produce overturned, attenuated high strain zones bounding lozenges of less deformed rock that locally preserve steeply-dipping bedding. Progressive transposition of the Paleozoic section in these shear zones leads to the de-

![Diagram](fig6.png)  
Fig. 6. Reconstruction of fault slivers above the Hat Mountain Fault from cross section H-H’ Note that this reconstruction was made using the almost certainly invalid assumption that displacement has been entirely within the plane of the cross section. The volume imbalance beneath the sliver of Supai Formation is attributed to out of section displacement. This reconstruction is meant to draw attention to the contrast in deformation style between the Bolsa-Martin package and Redwall-Supai package.
Fig 7. Recumbent folds in the area of the Silver Queen Mine. The locations of part of cross sections F-F', G-G', and H-H' are shown. Location of this figure is shown in Figure 3.

Development of folds with long, highly strained limbs parallel to the shear zone and short steep limbs close to the original orientation of the section (Cross sections G-G', H-H', I-I', J-J'). Bed-parallel layering is rotated into the long limbs by penetrative shearing strain or by heterogeneous deformation involving both rigid body rotation and penetrative deformation. Minor folds in the Coconino Quartzite provide small scale analogs for this style of transposition. The geometry of transposition is also well displayed along the Redwall-Supai contact in the canyon south of the Silver Queen mine. Penetrative strain accumulated in long limbs in the Supai Formation is localized into faults cutting massive dolomite in the Redwall formation.

Figure 5 shows the extent of transposed and non-transposed bedding. The Supai Formation starts to show signs of transposition as far southeast as Socorro Peak, but does not become penetratively transposed until the northeast side of the basin along Hidden Treasure Canyon. Kaibab Formation is transposed along the range front beneath the northwest-dipping fault zone at the gypsum mine southeast of Hidden Treasure Canyon (Fault 10, fig. 4). Kaibab is also transposed in southeast dipping shear zones along the range front northeast of Hidden Treasure canyon (Faults 22 and 13, Fig. 4). The transition to transposed bedding in all units above the Martin Formation corresponds with the zone of twisting northeast of Hidden Treasure Canyon. Shearing strain increases to the northeast, and sparse steep limbs preserving the original bedding in Upper Paleozoic rocks are found only in the Coconino Quartzite in the northeastern part of the map area.
Faults

Complex low-angle faulting is the dominant structural signature of this area. The south-vergent Harquahala thrust and associated shear zones are overprinted by younger faults and fabrics. Chert in the Kaibab Formation and siliceous concentrations in the Supai Formation commonly are deformed into rods that define a stretching lineation in zones of transposition along many of the low-angle faults. Stratigraphic separations and lineations in the carbonate units indicate that some low-angle faults have a significant southward slip component and others have a significant northeastward slip component. Some faults are associated with heterogeneous deformation in the Paleozoic section—a fault in one lithologic body disappears into a zone of penetrative deformation in an adjacent body. Low-angle Faults that cut into igneous and metamorphic rocks below and above the Paleozoic section are difficult to trace. Northwest-trending high-angle faults cut the system of low-angle faults, and appear to have polyphase displacement histories because of inconsistent separations of older faults. The possibility of pre-metamorphic faults that are folded or ductilely deformed is suspected (cross section M-M'). Because of the complexity of the faulting, in the following section, some key relationships and interpretations are discussed on a fault by fault basis. In a number of cases, faults are correlated across cross-cutting fault zones. These correlations are interpretative, and alternate hypotheses could be proposed. Rather than discussing all possibilities, this report discusses the reasons for the interpretation shown in the cross sections. The faults are referenced by number as shown in Figure 4.

Fault 0. Northwest-trending high-angle fault, post dates all structures in map area. Bending of strike of Paleozoic rocks to easterly trend adjacent to this fault is interpreted as drag. Tenahatchipi Detachment fault and other faults in crystalline rocks, as well as foliation in Tenahatchipi Gneiss show similar orientation changes near fault suggesting that rocks along the fault are consistently dragged in a right-lateral sense. Where exposed, the fault is characterized by a 2-5 m thick, non-indurated breccia and gouge zone.

Fault 1. Referred to as Golden Eagle thrust by Keith [1988]. This name is based on correlation of the structure with the mineralized fault at the Golden Eagle Mine in the Little Harquahala Mountains [Spencer et al., 1985], but it is highly unlikely that these are the same fault. Therefore the name is not used here. This fault cuts Proterozoic granite, and contains slivers of Bolsa Quartzite, and locally of Abrigo and Martin Formations. The fault zone is characterized by anastomosing, close disjunct cleavage in metasomatized granite. Feldspars in the granite (particularly plagioclase) are altered to sericite, which in thin section is observed to be oriented roughly parallel to the megascopic cleavage. Biotite is completely altered to chlorite. Strain textures in quartz are largely annealed. Gold mineralization at the Socorro mine is localized along this structure [Keith, 1988].

Fault 2. Where the fault is exposed at the southwest end of outcrops, is a fault zone containing slivers of Kaibab Formation within Coconino Quartzite, and dips to the southeast, but magnitude of dip is uncertain. The orientation of the fault in this area is probably modified by deformation in the drag zone adjacent to Fault 0. The solution to reconciliation of structures on cross sections AA- AA', A-A', and B-B' includes interpretation that this fault becomes a near-vertical, northeast-trending structure that contains slivers of Kaibab Unit 1 within Coconino Quartzite along section B-B'. This structure is cut by fault 6 along section B-B'. The fault loses definition within Coconino Quartzite to the northeast, and is lost.

Fault 3. Socorro Fault zone of Keith, 1988. Cuts faults 1, 2 and 6. Microdiorite dike (unit Tmd) on NE side of fault is apparently truncated at the fault, but dike may be coeval with fault.

Fault 4. Window in canyon bottom exposes Martin and Redwall beneath Supai Formation. Fault is sharp, no
fabric developed along fault. In cross section A-A', this fault is interpreted to be continuous with Fault 1, and may be continuous with Fault 6, forming a curviplanar fault with top to the northwest separation. See discussion of Fault 6.

Fault 5. This fault was recognized in the field where it offsets the contacts bounding the Bolsa, Abrigo, Martin and Redwall formations. In the field, the fault could not be traced through the Coconino Quartzite or Socorro Granite, but both of these units are highly fractured and permissive for the location of a fault. Faults 1, 2, and 6 are all at a lower elevation on the southwest side of the mapped trace and along strike projection of this fault. The existence of a continuous, northwest-trending fault would explain the vertical separation of these fault zones. Correlation of Faults 1, 2, and 6 across a thoroughly northwestern trending fault was the best solution found for reconciling the structures along cross sections A-A' and B-B'.

Fault 6. This is one of the most difficult faults in the map area to interpret. Two segments are clearly mappable. A clearly mappable fault segment bounds a sliver of Kaibab Limestone and Lower Mesozoic sedimentary rocks that crops out on the southwest side of the Hidden Treasure fault. This sliver presents the major enigma—it requires significantly more stratigraphic separation for its emplacement than is indicated by the separation between Supai Formation above the sliver and Martin Formation beneath it. After experimenting with a variety of interpretations, I decided that the best one is that the fault bounding the Kaibab sliver is linked southward through a zone of interleaved Supai and Coconino formations southward where a clearly mappable, gently northwest-dipping, fault on the south side of Socorro Peak, separates the base of Kaibab Formation to the northwest in its hanging wall relative to its footwall (sections B-B', BB-BB', C-C'). Along section BB-BB', the fault has two splays, consistent with the style of the structure in the Supai and Coconino.

Southwest of the Kaibab outcrops cut by Fault 6 (along the line of section B-B'), the location of Fault 6 in Coconino Quartzite is uncertain. A crush zone can be traced to a fault cutting off one on the slivers of Kaibab along Fault 2, and this probable fault zone offsets the Coconino-Supai contact. A low-angle fault that cuts the Redwall and Martin formations is at the right elevation and orientation to be a continuation of Fault 6, but a continuous fault could not be mapped through the Supai Formation. Given that Fault 6 contains a sliver of Kaibab Formation at its northern end, it is considered unworkable for the fault to just ‘die out’ southward. The solution hypothesized here is that Fault 6 does connect with the fault cutting Redwall and Martin formations, and this fault cut Abrigo Formation and Bolsa Quartzite as well, but does not produce a mappable separation of the contacts of these units. Fault 6 then is cut by Fault 5. The small stratigraphic separation observed along Fault 6 on the northeast side of Fault 5 requires that the total slip vector for Fault 6 is parallel to the intersection between the northeast-trending Paleozoic strata and the fault.

Cross sections AA-AA', A-A', B-B', and C-C' interpret that Fault 6 connects with Fault 1. The presence of slivers of Bolsa Quartzite along Fault 1 indicates the same sort of stratigraphic/structural separation on Fault 1 as is necessary to emplace the sliver of Kaibab Formation along Fault 6. I have not been able to invent a scenario for displacement on this fault that explains the origin of these slivers of younger rock sandwiched between older rocks in a satisfying way.

Fault 7. A ductile shear zone along the crest of Socorro Peak places partially transposed Supai Formation on Redwall Formation. The Supai Formation in the hanging wall is penetratively deformed and attenuated (Sections B-B' and C-C'). On the southwest end of Socorro Peak, the Bolsa-Martin sequence in the footwall is attenuated slightly beneath the shear zone. The shear zone in this area consists of interleaved Supai Formation, Redwall Limestone, and sheets of silicified rock that is at least in part Bolsa Quartzite but also probably includes hydrothermal quartz. Slickenside striae on silicified lenses trend about 135°. Interleaving of Supai Formation and Redwall-Martin formation can be explained with a two stage movement history, first to south (Martin on Supai), then to north (Supai on Martin). This fault dies out down dip into Supai Formation and is lost both on the northeast and southwest. Similar northwestward separation of units suggests connection with Fault 6. Fault 7 may merge into Fault 6, but the
fault bounding the sliver of Kaibab Formation near the Hidden Treasure Fault must be a separate fault. Correlation of Fault 6 with Fault 1 requires that this low angle fault underlie Socorro Peak (section C-C’), and that Fault 7 is a higher, separate fault.

Fault 8. This fault is associated with the southwestern part of a ‘twist’ structure in the lower Paleozoic rocks northeast of Socorro Peak. The fault disappears into complexly deformed Supai Formation on the south and into Socorro Granite on the north.

Fault 9. Well exposed, planar, sharp fault with thin breccia zone. Cut by Fault 6 on west, disappears into Coconino on east. This fault cuts overturned section, and has reverse structural separation but normal stratigraphic separation. The fault is shown on section D-D’. No correlative fault can be identified on the northeast side of the Hidden Treasure fault, or in the hanging wall of Fault 6.

Fault 10. Gypsum within the Kaibab Formation southeast of the Hidden Treasure Fault is interpreted to occupy a shear zone (section C-C’). The boundaries of the gypsum body are not well enough exposed to test this hypothesis. A fault placing Kaibab Unit 4 on Kaibab Unit 3 about 2000 feet (600 m) southwest of the mine (section BB-BB’) has a similar orientation and is tentatively interpreted as a continuation of this fault.

Fault 11. Southwesternmost exposure of hanging wall of the Harquahala thrust. Fault zone is strongly cleaved chlorite-sericite semischist. Pyrite cubes (altered to brown limonite) in this rock have strain shadows suggesting that they formed before or during a ductile deformation event. The fault superposing the retrograded mafic gneiss on transposed Kaibab Formation (Unit 4?) is interpreted to be a composite of the Harquahala Thrust and younger low-angle faults (see discussion of Fault 24).

Fault 12. A moderately dipping fault superposes chloritically altered, mylonitic, fine-grained granodiorite on transposed Kaibab Formation in the major wash on the northeast side of the Hidden Treasure Fault (Fault 17). The fault zone is a 10-20 cm thick crush zone. Underlying Kaibab is silicified and iron stained. The hanging wall granodiorite is unlike rocks seen immediately above the Harquahala thrust, and grades up into a sedimentary breccia derived from the granodiorite (section E-E’). These relationships indicate that this fault is completely different than Fault 11 on the southwest side of the Hidden Treasure Fault. It is interpreted as a detachment fault, and correlated with a fault inferred to superpose Tertiary volcanic rocks on gneisses in the hanging wall of Fault 11 (section C-C’). Fault 12 is hypothesized to swing to a southeast strike eastward such that crystalline rocks above the Harquahala thrust in the southeast corner of the map area are in footwall of the detachment fault. This is based on the lithologic disparity between the granodiorite in the hanging wall of Fault 12 and other crystalline rocks observed in the hanging wall of the Harquahala thrust. Fault 12 must cut Faults 22 and 24 in this scenario.

If the interpretation that Fault 12 superposes Tertiary volcanic rocks on pre-Tertiary rocks on the southwest side of the Hidden Treasure fault, the contrast in footwall rocks beneath Fault 12 across the Hidden Treasure fault is striking. On the northeast, Fault 12 cuts upright Kaibab Unit 1, that is transposed in a thin zone beneath the fault, but overlies Coconino Quartzite on a mostly intact depositional contact. On the southeast side of the Hidden Treasure fault, Fault 12 cuts gneissic rocks above a composite ‘Harquahala thrust’, which in turn overlies penetratively deformed Kaibab Unit 4. Fault 12 thus cuts rocks in significantly different structural and stratigraphic positions. These relationships are interpreted to require that the Hidden Treasure fault was active both before and after Fault 12.

Fault 13. Fault not exposed; repeats Coconino-Kaibab contact. Limestone of Kaibab Unit 2 is transposed in the footwall, but Unit 1 dolomite below that is not transposed. A sliver of Lower Mesozoic sedimentary rocks are the structurally highest rocks exposed in the footwall. Rocks along the range front in this area are apparently dragged down and/or to the southwest adjacent to Fault 22. Fault 13 might thus be a reoriented segment of Fault 16 (suggested by slivers of JTs), or part of Fault 22.

Fault 14. Northwest dipping fault zone repeats base of Coconino quartzite (section E-E’). Relative simple thin
fault zone adjacent to Hidden Treasure Fault contains 5 m thick sliver of Kaibab Unit 1. The fault bifurcates to the northeast, to contain a sliver of tightly folded(?), tectonized Kaibab Unit 1 with Kaibab Unit 2 in the core of the fold(?). The apparent fold might be due to tectonic interleaving. The lower strand of Fault 14 disappears southward into a zone of transposed/tectonized Kaibab Unit 1. The upper strand intersects the Fault 19 zone, which here coincides with a ‘twist’ zone in the Kaibab Formation (see Folds section). Fault 14 has normal separation. I cannot correlate it with any structure on the southwest side of the Hidden Treasure Fault.

Fault 15. Sharp fault contact repeats the top of the Redwall Limestone. The structurally low part of the fault, near the Hidden Treasure fault, dips moderately northwest. Upward, as the fault approaches Fault 16, it is folded over to dip gently southeast, and loses definition in tectonized Supai Formation beneath Fault 16.

Fault 16. Subhorizontal ductile shear zone that separates Coconino-Supai contact northwestward in the hanging wall relative to the footwall. Accordant, flat-topped ridges in the basin northeast of the Hidden Treasure fault are defined by this fault surface. Slivers of Lower Mesozoic sedimentary rocks or Jurassic volcanic rocks are present in the fault zone in several places, and are considered characteristic of this fault. These rocks are now sericite-chlorite schist or phyllite with multiple overprinting cleavages. A footwall splay off of Fault 16 near Fault 15 resembles Fault 7 in the way it emplaces transposed Supai Formation upward across Redwall Limestone (section E-E’). Fault 16 may correlate across the Hidden Treasure Fault with Fault 7 or (and?) Fault 6. Fault 16 is correlated with Fault 18-20-21, which lies at a higher elevation on the northeast side of Fault 19.

Fault 17. Hidden Treasure Fault. Name proposed by Varga [1977]. This is a steep-to-vertical, northwest-trending fault. Coconino Quartzite adjacent to the fault is strongly brecciated. Carbonate units along the fault appear to be brecciated and recemented, except at the immediate fault surface. Comparison of cross sections D-D’ and E-E’ requires that this fault has a complex history, at the minimum it was active before and after detachment Fault 12. The kinematics of the zone of wedging where the Hidden Treasure Fault cuts the lower Paleozoic section, and its relationship to the ‘twist’ zone there have not been resolved. The fault could not be traced into Socorro Granite. The similarity of orientation and alignment on one splay from the Hidden Treasure fault suggest the possibility that Fault 35 might be kinematically linked with the Hidden Treasure fault (see discussion of Fault 35)

Fault 18. Shear zone similar to Fault 7. Hanging wall Supai Formation is transposed near fault. Klippen of Bolsa and Martin Formation on top of Supai are probably in the hanging wall of southwestern continuation of Fault 30. Fault 18 in interpreted to be connected with Faults 20 and 21 to form a single fault bounding a klippe of Supai and Coconino formations. See discussion of Fault 20.

Fault 19. This is a fault zone interpreted to exist to explain several perplexing relationships. Fault segments recognized in the field cut the Bolsa Quartzite, Martin Formation and Fault 16 at the northern end of the trace, bound the klippe of Coconino and Supai above Fault 18-20-21, and juxtapose overturned Coconino and Kaibab formations against lower Kaibab at the south end of the fault trace. Several small faults that offset the base of the Bolsa Quartzite are interpreted to be related to this fault zone. The chaos zone along section K-K’ is interpreted as a zone of tectonic slivering and mixing along this fault zone. Blocks of Redwall dolomite, Martin formation and Coconino(? ) quartzite are mixed in Supai Formation along this zone for 700’ south of the area mapped as chaos. Trace of fault where it juxtaposes Supai Formation against Coconino on the northeast demonstrates that this part of fault is steeply dipping. Connection of the fault zone from where it juxtaposes Coconino against Coconino to the recognized fault between upright and overturned Kaibab is speculative. Fault 16 is correlated with Fault 18-20-21 across Fault 19 indicating a vertical separation of about 300 feet (100 m), down on the southwest. Association of this fault with a zone of ‘twisting’ in Paleozoic rocks on its northeast side suggests the fault is kinematically linked with the ‘twist’ structure, similar to Fault 8, and perhaps part of the Hidden Treasure fault.
Fault 20. Subhorizontal fault within Coconino Quartzite, contains thick sliver of tectonized Kaibab Formation. Upper contact of Kaibab sliver is interleaved with Coconino in some places. Interpreted to be cut by fault 19 on the southwest. Cannot be traced through Coconino on northeast after Kaibab sliver pinches out. Fault 20 is interpreted to connect with Fault 21 as part of Fault 18-20-21, which forms the base of a klippe of Coconino and Supai formations.

Supai Formation in the hanging wall of Fault 18-20-21 is silicified and epidote altered. Coconino Quartzite near the steep contacts with the Supai also contain abundant epidote, making locating the Coconino-Supai contact difficult. The alteration appears to post-date structures responsible for repeating the Coconino-Supai contact in this klippe. The interpretation selected for cross sections F-F' and I-I' is that the northwestern boundary (Coconino on northwest, Supai on southeast) is a fault, and the southeastern boundary is a sheared depositional contact.

Fault 21. Interpretation that Faults 18 and 20 are part of a single low-angle fault requires that fault 20 have a continuation to the northeast beyond its disappearance into Coconino Quartzite. Fault 21 is this continuation. This fault may be at the base of Supai Formation in the klippe, or at the top of Supai Formation in the canyon (section F-F'). The Coconino-Supai-Coconino sequence beneath Fault 21 is in a body of strongly sheared rock, and distinguishing sheared depositional contacts from fault repetitions is metaphysical given the lack of facing indicators. As show in cross section F-F', the southern boundary of Supai Formation in this canyon bottom has a steep dip and appears to be a depositional contact preserved in a relatively low-strain zone.

Fault 22. Sharp fault zone superposes northwest-facing Redwall, Martin, and Bolsa formations on top of Supai Formation. Faults bounding the two klippen northeast of the Silver Queen Fault are curviplanar. This fault is associated with a northwest-facing recumbent drag fold in underlying rocks, and it may represent a faulted overturned fold limb in a northwest-vergent structure. The problem, of course, is that given the present distribution of rocks in the footwall, the stratigraphic separation requires southward displacement. This may be another composite structure with radically different transport directions. The stratigraphic juxtaposition suggest correlation with Fault 30 on Hat Mountain.

Fault 23. Silver Queen Fault. A northwest-trending, post-metamorphic high angle fault. Like the Hidden Treasure Fault, structures in the Paleozoic rocks can not be matched across the fault. The base of the Bolsa Quartzite and the Harquahala ‘thrust’ composite fault both show similar magnitudes of right separation across the fault, but the stratigraphic/structural position of the Harquahala ‘thrust’ changes significantly across the Silver Queen Fault.

Fault 24. Harquahala ‘thrust’ composite fault. Northeast of Silver Queen Canyon, gneisses of the hanging wall of the Harquahala thrust (Fault 31) are superposed on Supai and Coconino formations along a sharp, planar fault zone with some silicified, iron-stained (black) breccia. The style of this fault is typical of low-angle normal faults in the region, and it is interpreted as a composite fault probably equivalent to Fault 31 (Harquahala thrust), Fault 33, and probably a younger normal fault associated with Fault 12.

Fault 25. Fault rocks in the fault that superposed this sliver of gneiss on Kaibab and Coconino formation contains anastamosing close disjunct cleavage similar to Fault 27, and is interpreted to be a non-excised remnant of that fault.

Fault 26. Fault bounding window through Harquahala plate into Coconino and Supai Formation. Style of fault rocks suggests correlation with Fault 27.

Fault 27. The fault that superposed Proterozoic rocks on Paleozoic Rocks on the southeastern side of the range is a composite structure resulting from two or more periods of deformation. The gently NE-dipping post-thrust Fault 33 intersects the Harquahala thrust (Fault 31) at a very low angle near the crest of the range south of the White Marble Mine. Displacement on the Hat Mountain Fault (Fault 29) must also
be accommodated across this fault. The style of tectonites along the Harquahala thrust changes from mylonite with a well-developed L-S fabric to S-tectonite with a close, anastomosing spaced cleavage in the area of its intersection with faults 32 and 33.

Fault 28. Ductile shear zone superposes Coconino Quartzite on Redwall Limestone on northeast side of tectonic window in canyon bottom (Cross sections H-H', J-J', and M-M'). In the hanging wall, the transposed Coconino-Supai contact is truncated at the fault at almost the same place the Supai-Redwall contact is truncated in the footwall, and the fault must become a cryptic high strain zone within highly strained and transposed Supai Formation. This is the structurally lowest slide exposed on the northeast side of the Silver Queen Fault. Top-to-the-northwest stratigraphic separation (of vertical Paleozoic strata) is consistent with the separation on the Hat Mountain fault (Fault 29), Fault 18-20-21 between the Silver Queen and Hidden Treasure Faults, and Fault 1-6 on the southwest side of the Hidden Treasure Fault.

Fault 29. Hat Mountain Fault. Subhorizontal, curviplanar, sharp fault contact placing a klippe of highly deformed Paleozoic rocks and Proterozoic granite on top of Proterozoic granite. Strong fabric is not developed in granite adjacent to the fault, but carbonate units in the hanging wall are tectonized, transposed, and locally chaotically folded. Stratigraphic separation is top-to-the-northwest, 3000-4000' (900-1200 m), increasing to the northeast. The nature of the contact between Bolsa Quartzite and Proterozoic granite (Yg) on the northwest side of the klippe can not be confidently determined. The intersection of the Hat Mountain Fault and the stratigraphic base of the Bolsa Quartzite is probably at or near the exposed contact (compare interpretations on map and cross sections H-H' and I-I'). The Hat Mountain Fault is interpreted to be truncated by Fault 33 (see discussion of Fault 33).

Fault 30. Rocks in the hanging wall of the Hat Mountain Fault (Fault 29) are cut by a series of imbricate low angle faults that have top-to-the-southeast stratigraphic separations (Cross sections G-G', H-H', Figure 6). These faults are similar in style to the Hat Mountain Fault; they are generally sharp, and lack strong fabric development associated with the fault surfaces.

Fault 31. Harquahala Thrust. See description in introduction. L-S tectonites along this fault in the northeastern part of the map area contain south-trending lineation and top-to-the-south S-C fabric.

Fault 32. White Marble Mine Fault #2. The only clearly distinct segment of this low-angle normal fault is in the upper part of the canyon above White Marble Mine, where a moderately northeast-dipping fault cuts the flat fault at the base of Supai Formation (Fault 29 or 33?), and drops it beneath the floor of the canyon (cross section J-J'). To the southwest, this fault merges with Fault 33 to form Fault 35. To the northeast, it merges with Faults 34 and 31 (Harquahala thrust). Exposures are not good enough on these north-facing slopes to determine which faults are overprinted by brittle structures characteristic of Fault 32. Based on projection of its dip, it is suggested that Fault 32 cuts across Faults 34 and 31 and into the hanging wall of the Harquahala Thrust, but the fault might equally well merge with Fault 31.

Fault 33. White Marble Mine Fault #1. A northeast-dipping normal fault is interpreted to cut the Hat Mountain Fault east of Hat Mountain (cross section N-N'). The existence of a separate fault is based on a shattered zone in the Supai Formation, and a change to a more brittle fault style. This fault merges southward with Faults 31 and 34 to form Fault 27. The junction of these faults is on strike with a steep, northeast-trending fault that offsets the Hat Mountain Fault on the southeast side of Hat Mountain and drops its hanging wall down on the northwest (cross section H-H'). This northeast-trending fault intersects with other minor(?) faults in a complex intersection zone with Faults 33 and 31 (cross section J-J'). Fault 33 is within a zone of northwest-trending, distributed minor normal faults. Many of these faults are mapped as short segments, and more such faults exist but are not mapped. These faults cut Miocene mafic dikes (Tmd).
Fault 34. In the White Marble Mine area deformation becomes penetrative in all rock units, and a sliver of Proterozoic biotite granitoid (Yh and Yg) is sheared southward across the Paleozoic section (cross section J-J'). The steep, depositional, basal contact of the Bolsa Quartzite can be traced uphill into the shear zone adjacent to the Harquahala thrust, where it flattens out and becomes the fault at the base of the granitoid sheet.

Fault 35. Composite normal fault, includes fault 32 and 33. These faults excise Paleozoic rocks in the hanging wall of the Hat Mountain fault, such that only a thin sliver of Bolsa Quartzite and Martin Formation is present between granite (Yg) in the hanging wall of Fault 34 and granite (Yg, XYgg) in the footwall of the Hat Mountain Fault.

Fault 36. Moderately northeast dipping fault can be mapped superposing fine-grained granodioritic rocks (XYgg) on Socorro Granite (Ys). Fault zone characterized by sericitic anastamosing disjunct cleavage similar to fabric along Fault 1. Fault 36 may be a northwestern continuation of the eastern splay of the Hidden Treasure fault, but the cleavage observed along Fault 36 was not observed along the splay of the Hidden Treasure Fault, leading to the interpretation that they are separate faults.

Tenahatchipi Detachment fault. A north-trending, east dipping detachment fault can be mapped along the wash on the south side of Tenahatchipi Pass. This fault zone consists of 1-3 m of crushed rock and gouge. Chloritic alteration is extensive, particularly in biotite or hornblende rich rocks along the fault. This fault drops granitic rocks an overlying Paleozoic rocks of the Centennial thrust plate down on the northeast (fault is labeled on geologic map).

Interpretation

Paleozoic and Mesozoic strata record a more complex deformation history than the surrounding crystalline rocks. This is probably due in part to concentration of strain in the more readily deformed quartz and calcite-rich sedimentary rocks, and to the fact that the existence of stratigraphic markers allows recognition of structures that would go unnoticed in massive crystalline rocks.

Deformation that produced the steeply dipping, northeast-trending belt of Paleozoic strata pre-dates the Harquahala thrust in the map area, and regionally predates the emplacement of recognizable thrust sheets. Similar strike belts in the Granite Wash Mountains and Little Harquahala Mountains have been interpreted as the steep limbs of large-scale, top-to-the SE-vergent folds related to crustal contraction [Reynolds et al. 1986; Laubach, 1986; Laubach et al., 1989; Richard, 1982]. In this map area, no firm evidence to document the existence of southeast-vergent recumbent folds was found. Large-scale overturning of Paleozoic strata in the White Marble Mine-Socorro Mine area is spatially associated with the Harquahala thrust. Minor southeast-facing recumbent folds in the southwestern part of the strike belt are associated with faults (e.g. Fault 6) that probably have north-south to NNE oriented, subhorizontal slip vectors. If a steeply dipping block of strata is sheared in a subhorizontal shear zone, folds formed will tend to be oriented parallel to the strike of the strata (Figure 8). Given the upward decrease of the dip of strata in overlying Apache Wash (McCoy Mountains?) formation in all the areas where steeply dipping, NE-trending belts of Paleozoic strata are observed [Spencer et al., 1985; Reynolds et al., 1991; Richard and Spencer, 1994; Richard et al., 1993], it seems reasonable to consider the possibility that tilting is related to normal faulting during deposition of the Jurassic-Cretaceous clastic sequences.

The most prominent deformation of Paleozoic rocks in the map area is shearing in the south-vergent Harquahala thrust zone that resulted in the transposition and overturning of steeply southeast-dipping strata.
Figure 8. Model for folding of Paleozoic rocks beneath Harquahala thrust.

Figure 9. Strain during development of large scale extensional crenulation in steeply dipping Paleozoic strata. Upper part shows finite strain ellipse for progressively increasing plane shear strain. Lower part is a schematic view of the style of deformation in the middle and upper Paleozoic section. Arrows show facing direction of stratigraphic sequence. At A, the steeply dipping strata are in the field of incremental shortening and undergo slight buckling. At B, the orientation of the layering passes into the field of incremental extension. Between B and C, shear zones nucleate, at least in part on the limbs of buckle folds. Extension of the layering between C and D is accommodated by high strain along shear zone within which the layering is transposed. Lower strain domains preserve steeply dipping, but overturned stratigraphic sequences.
The geometry of the transition from mostly upright to mostly overturned beds is not consistent with a simple large-scale recumbent fold. Twisting of beds from upright to overturned along strike suggests overturning by entrainment in a shear zone oblique to the orientation of bedding anisotropy (Figure 8). The persistent steep dips in the Bolsa Quartzite and Martin Formation indicate that these units are less strained than the Redwall and overlying formations. This is interpreted to reflect their mechanical competence and the effects of a strain shadow adjacent to the underlying Proterozoic granitoids. The buckle folds in these relatively less strained lower Paleozoic strata suggests that the Paleozoic strata were originally oriented in the flattening field of the deformation. With progressive deformation, the more highly deformed formations above the Martin Formation were apparently rotated into the field of finite extensional strain [Ramsay, 1967] resulting in a large scale extensional crenulation [Platt and Vissers, 1980] (Fig. 9). Upper Paleozoic rocks, particularly the upper Redwall Limestone and Supai Formation have been transposed and sheared to form an upside-down lithologic sequence in the northeastern part of the map area.

The numerous gently dipping faults with northward separation are interpreted to be younger than the Harquahala thrust deformation. This interpretation is based on the observation that northerly-vergent minor folds with associated southwest-dipping cleavage are commonly the youngest minor structures observed in outcrop. The Hat Mountain Fault intersects the Harquahala thrust in a zone of overprinting normal faults, and the fabrics developed along faults in this area are not distinctive enough to allow confident identification of crosscutting relationships between the numerous gently dipping faults.

Similarity of separation suggests correlation of the Hat Mountain fault with Fault 18-20-21, Fault 16, and Fault 6-1. The Hat Mountain Fault can quite confidently be correlated with Fault 18-20-21. The klippen of Bolsa Quartzite and Martin Formation above Fault 18-20-21 are analogous to Fault 30 above the Hat Mountain Fault. Fault 16 and Fault 6-1 contain slivers of Mesozoic rock that are absent along the Hat Mountain Fault and Fault 18-20-21, but the similarity of style and orientation favor correlation of these structures. The fault that repeats the Supai-Coconino contact in the hanging wall of Fault 18-20-21 is not recognized in the hanging wall of Fault 16, but would apparently project into the air south of where the hanging wall of Fault 16 is continuously exposed. Fault 6-1 is perplexing because of the slivers of young rock interleaved between older units (Kaibab in Redwall, Bolsa in Socorro Granite). Slip on this fault system must be significantly greater that is indicated by the stratigraphic separations, probably including more than one phase of movement, and significant slip parallel to the intersection with formation contacts.

Mineralization

Several mines in the area have produced between 100 and 2000 oz. gold, along with up to about 7000 oz. of silver. These are mostly located along shear zones within Paleozoic formations or between Paleozoic formations and underlying granite. Extensive, low-intensity sericite-silica alteration, with minor disseminated pyrite, is associated with the mineralized areas. In a number of locations, evidence has been observed to suggest that the sericite-silica-pyrite alteration formed before or during at least the youngest cleavage-forming event. At the San Marcos Mine, about 2.7 miles (4.4 km) NNW of the Socorro Mine, mineralization is associated with a subhorizontal ductile shear zone within a similar cleaved sericite-silica alteration zone. Sericite from the shear zone has yielded an \(^{40}Ar/^{39}Ar\) plateau age of 55 Ma [Richard et al., 1998], suggesting that the exten-
sive, low-intensity, sericite-silica-pyrite alteration, and perhaps the shear zones, may be late Laramide in age. A Jurassic age for the original sericite-silica-pyrite alteration, followed by Laramide cleavage formation, is also consistent with the data available. Most of the actual production appears to have been from oxidized, brittle shear zones, typically containing red earthy hematite. The major mines (except the poorly located Why Not) are located along or close to northwest trending high angle faults that are the youngest structures recognized, and are at least partly Miocene (post-detachment faulting) in age.

A working hypothesis proposed for gold mineralization in the area is that a regional, extensive, but low-intensity sericite-silica-pyrite alteration event was the first mineralizing event, and perhaps introduced disseminated gold. This alteration event may predate or have accompanied cleavage formation and low-angle faulting, which is bracketed in age between about 160 (age of Jurassic volcanic rocks [Reynolds et al., 1987]) and 55 Ma (above reported date). Renewed hydrothermal activity in Tertiary time, perhaps driven by thermal gradients related to crustal extension [Spencer and Welty, 1989] remobilized gold, concentrating it in favorable locations to produce ore-grade accumulations. Intersections between Miocene northwest-trending high angle faults and pre-existing moderately to gently dipping shear zones appear to have consistently provided a favorable environment for gold accumulation. Lithologic environments favorable for gold deposition include dolomitic carbonate rocks of the Martin and Kaibab formations, and Bolsa Quartzite in the vicinity of low-angle faults.

**Mines**

1. **Socorro Mine.** Keith [1988] provides a detailed description of mineralization in the area of the Socorro Mine, and much of the following description is based on his report. The Socorro Mine shaft is collared in granite just below sliver of Bolsa Quartzite along Fault #1 (Golden Eagle Thrust of Keith [1988]). The inclined shaft is 375 feet long, with 2300 feet of drifts developed from it. Gold mineralization is concentrated along Fault #1, and a disseminated gold anomaly is documented by Keith [1988] in the Bolsa Quartzite that forms the ridge above this fault. Alteration includes supergene hematite-clay and hypogene quartz-sericite-pyrite in the Bolsa Quartzite, quartz veining in the underlying biotite granite (Unit Ysb), and epidote chlorite alteration in microdiorite dikes (unit Tmd; not observed by the author). Gold mineralization is associated with zones of pervasive sericitization. Highest gold values are associated with rock that contains red earthy hematite and limonite/goethite replacing pyrite cubes. Keith [1988] reports that microdiorite dikes (unit Tmd) that cross the gold anomaly are moderately to strongly chloritized and epidotized, contain moderate to strong hematite and goethite along fractures, and locally contain small limonite after pyrite cubes. He relates gold mineralization in the area to the microdiorite dikes. Keith [1978] reports that mineralization was located along an irregular, lensing fissure vein in quartzite, limestone and shale, intruded by Laramide granite and related dikes. The vein was described as vuggy, brecciated, and recemented by silica and jasper. No evidence was observed in the exposures around the mine to affirm the existence of a Phanerozoic granitic rock in the immediate area, but fine grained granodiorite and granite mapped as JKg does intrude granite of the Socorro suite (units Ysm and Ysb) as close as about 3000 feet (900 m) north of the mine, and in the area north of the Mars and Mescal mine. Keith [1988] reports that intermittent operation between 1905 and 1914 yielded a minimum of 660 oz gold and 370 oz. silver. Keith [1978] reports production of 960 oz. gold, 480 oz. silver, and some lead between the early 1900’s and 1960.

2. **Socorro Mining Open Cut.** Small open pit in Bolsa Quartzite at the center of the Socorro Reef gold anomaly of Keith [1988]. In 1982, rock mined from this site was placed on a leach pad located on the old Socorro Mine dump, on top of material from the Henry Bell claims and the dump material from the Socorro Mine. 37.7 oz. of gold were reportedly produced from this project [Keith, 1988]. Alteration
and gold mineralization in the Bolsa Quartzite is related to the disseminated gold anomaly associated with the Socorro Mine.

3. **Henry Bell Prospect.** North-trending, east-dipping fault zone intersects Fault 3 (Fig. 4). There are a series of trenches and cuts in Supai Formation and massive Martin or Redwall Dolomite. Curvilinear fault underlies klippe of Martin Formation on top of Redwall Limestone. This fault is flat at its southern end (uppermost Martin on Supai), but curves up to dip 40° at the north end of the klippe where Martin overlies Redwall. Northwest and northeast striking moderate to high angle faults both cut the low-angle fault bounding the klippe. Northeast-striking faults appear to be most strongly mineralized in outcrop. Mineralization includes quartz veins in massive brown dolomite. Dolomite appears to have been brecciated and recemented. Northeast-striking, northeast-dipping faults (related to Fault 3?) are the youngest structures. Nearby northwest-trending mafic dike (Tmd) does not look altered. Keith [1988] suggests that production of 22 oz gold, 100 oz silver, and 50 lbs copper reported from the Socorro Mine in 1934-1935 probably came from the Henry Bell.

4. **Why Not (syn. Iron Door 3 & 4).** Shear zone placing Supai Formation on Redwall and Martin Formation (Fault #7, Fig. 4). Silicified blocks in the shear zone are at least in part Bolsa Quartzite, but also include hydrothermal silica. Dolomite blocks in the zone contain planar quartz veins 5-20 cm thick, trending 080 to 100° with steep dips. The veins end at contacts between the relatively brittle dolomite blocks and enclosing limestone or phyllite, suggesting that the veins formed during the ductile deformation event. Bolsa Quartzite contains lenses of magnetite-sericite phyllite. Sericitic, cleaved Supai siltstone layers contain limonite after pyrite cubes with strain shadows, again suggesting pyrite formed before or during cleavage formation. Gold mineralization (some visible gold) is associated with red earthy hematite oxidized zones that are concentrated along steep brecciated zones. Keith [1988] reports that production reported by Kuisto & Smith, A.E. Lang & Gilbert, A.E. Lang, and T.F. Johnson between 1932 and 1938 from the Why Not mine probably came from numerous pits and shafts on the ridge east and northeast from this location. Total production reported was 233 oz gold, 689 oz silver, and 1612 lbs copper [Keith, 1988]. These small mines are probably all associated with the same shear zone (Fault #7, fig 4).

Keith [1978] places the Why Not, Clipper, and Gold mine groups in center and E. Center, sec. 30, T 5 N, R 11 W. This location may correlate with the mine shown on the USGS Socorro Mine 7.5' quadrangle about 2000 feet (600 m) southwest of the Harquahala Gypsum mine. He reports production of 1220 oz gold, 666 oz silver, and 13300 lbs copper from this (these?) location(s) between 1932 and 1939. The depth of mine shafts and the size of dumps at the mines, and the lack of apparent mineralization in outcrops seen in this area is not consistent with this magnitude of production Keith [1978] reports, and Keith’s [1988] interpretation of the location of the Why Not is considered more reliable.

5. **Mars and Mescal Mine (syn. Iron Door 1 & 2, Old Noel, Nuevo Mundo Mountain Mines).** George Campbell of Salome, Arizona reported (personal communication, 1987) that the ore is “limonite or earthy hematite,” and has been completely stripped out. Three shafts driven along shear zone between massive dolomite of middle Redwall and white to varicolored limestone marble of upper Redwall Limestone. Tectonite fabric in upper Redwall Limestone contains stretching lineation oriented north-south. Center of three shafts is 800' deep (George Campbell, personal communication, 1987). Several north- to northwest-trending high angle faults intersect the shear zone, and the thickness of middle Redwall preserved between the Martin Formation and upper Redwall changes across these zones. Mineralization visible in outcrop is concentrated in these intersections, consists of hematite staining, and sparse limonite after pyrite. The northwest-trending zones form discontinuous discrete fault segments linked by masses of brecciated rock. Two types of dikes intrude the carbonates near these shafts: dark green dikes with sericitized feldspar phenocrysts, and fine-grained, sericitized aplite dikes (related to JKg?). Both types of dikes are strongly cleaved. Alteration sericite is oriented parallel to cleavage, indicating that some alteration pre-dates or accompanied cleavage formation. Keith [1978] reported “irregular lenses of oxidized copper mineralization with silver and gold in brecciated diorite,
cherty limestone, and heavy batches of iron oxide along a fissure zone bordering a diorite dikes in a complex Precambrian granite-schist, alternating with altered distorted... limestone. Series of northwest striking diorite dikes along fissure zone."
The depth of the shaft suggests it may penetrate Fault #8 (Fig. 4). The granite-schist described by Keith [1978] is probably the cleaved dike rock observed at the surface. The alternating granite and limestone may be due to dikes of granite along a fault zone. Keith [1988] reports production of 16 oz. gold, 56 oz. silver, and 28,865 lbs. copper from this mine in 1916-1918. Keith [1978] reports production of 16.5 oz. gold, 33 oz. silver, and 24200 lbs. copper for the same period.

6. Hidden Treasure Mine (syn. Lucky Helen #1, Magic Group). Horizontal tunnel collared in Kaibab unit 1, but most of the rock on the dump is Coconino Quartzite, which underlies the Kaibab here. Rock visible in tunnel and in waste dump shows no apparent mineralization except possible sericitization of phyllosilicates in bedding partings of Coconino Quartzite. At the tunnel entrance, the Kaibab is strongly sheared and transposed. Several other small shafts and prospects in this area explore the contact between the Kaibab Formation and Coconino Quartzite. Keith [1978] reports that free gold occurred with silver in cellular masses of limonite and calcite in seams and tabular replacements along a shear zone in quartzite and silicified limestone. Minor chrysocolla, oxidized lead and zinc minerals and manganese oxides were associated with the ore. Alteration included silicification and minor sericitization of wall rock. Keith [1978] reports production of 1686 oz. gold and 6922 oz. silver, along with minor copper, lead, and zinc between 1932 and 1967. The dump at the main mine tunnel is large enough to be consistent with this production, but the ore rock must have been carefully hand picked and taken from the site. The Hidden Treasure and other shafts and adits in the immediate area appear to be associated with several northwest-trending minor high angle faults that cut the Coconino-Kaibab contact.

7. Mineralized area east of Hidden Treasure Mine #1. Fault oriented ~060/27SE cuts Kaibab Formation; fault contains banded onyx, and brecciated marble tectonite with barite cement. Deformation in Kaibab is very heterogeneous, with dolomite boudins enclosed in chaotically folded marble. Extension veins with barite fill are oriented 147/66NE.

8. Mineralized area east of Hidden Treasure Mine #2. Along the range front, dolomite in Kaibab Formation contains abundant fractures with black (MnO ?) powdery filling. The dolomite in this area contains abundant white mica (sericite?) on fracture surfaces.

9. Harquahala Thrust south of Hidden Treasure Mine. Fine-grained mafic gneiss intruded by aplitic leucogranite in hanging wall of Harquahala 'thrust' composite fault is altered to quartz-chlorite-sericite phyllite. Limonite after pyrite cubes are disseminated throughout the altered hanging wall rock. Cubes are deformed in cleavage, broken by arrays of internal fractures similar to (but smaller than) those that form in conglomerate clasts in basal Mesozoic sedimentary rocks (JRs) beneath the thrust. The cubes have calcite filled extension fractures along their margins. Alteration predates or formed with the cleavage in this zone.

10. Silver Queen Mine. A small body of highly cleaved, sericitized granitoid is present along the fault that superposes Bolsa and Martin formation on Supai Formation (Fault 22, Fig. 4). It contains quartz and feldspar phenocrysts up to 5 mm in diameter in a fine-grained sericitic phyllite matrix. This granitic rock grades into a medium fine-grained hornblende diorite with fine-grained, chloritic margins. The granitic rock looks like Jurassic quartz porphyry (Jqp). The body is apparently derived from rock that intruded Martin Formation before cleavage formation. Along the fault between Martin Formation and Supai Formation is a 1.5-2 m thick quartz-calcite vein that seems to have been the target of exploration for several small tunnels and prospects in the area. No base metal mineralization is visible in the area. The US Bureau of Mines MILS data base reports that the Silver Queen was a tungsten prospect.

11. Prospect, upper Silver Queen Canyon. A 2-4 m thick ledge of massive brown goethite (?) follows bedding in the middle part of the Redwall Limestone along the north side of this canyon for ~100 m. A prospect in the bottom of the wash exposes drusy barite filling open space in massive hematite/goet-
White Marble Mine. Martin Formation and lower Redwall Limestone in the hanging wall of the White Marble Mine normal faults (Faults 32 and 33, Fig. 4) and footwall of the Harquahala Thrust (Fault 31, Fig. 4) are altered to a medium- to fine-grained white marble in this area. Dolomitic rocks that contained silica or clays are dolomite(+calcite?)-talc-tremolite-white mica granofels. The contact between Martin Formation and Redwall Limestone can not be recognized due to the alteration of the rocks. Small pods of granodiorite that appear to intrude Martin Formation just east of the quarry may be related to the more advanced metasomatism/metamorphism of carbonate rocks in this area. Supai Formation on the mountain south of the quarry (in the footwall of fault 32, Fig. 4) is altered to calcite-silica-epidote hornfels.

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DESCRIPTION OF MAP UNITS

**d** Disturbed surficial deposits (Holocene) — Gravel, broken rock and rearranged surficial deposits on mine dumps.

**Qs** Surficial deposits (Quaternary) — Non-indurated to poorly indurated sand, silt, and gravel. Poorly bedded, with abundant channeling. Includes deposits in modern drainage channels and older alluvium now being dissected in the present drainage.

**QTs** Old alluvium (Quaternary or Tertiary) — Massive, unorganized cobble to boulder conglomerate, with light tan calcareous sandstone matrix. Generally coarser grained and more indurated than Qs unit.

**Tch** Chaos (Miocene or Miocene) — Mixed Paleozoic limestone, diorite, pegmatite, mylonitic biotite granitoid and deformed, altered porphyritic biotite granitoid; poorly exposed on pediment. Outcrops in washes suggest mixing by interleaving along brittle faults. Only present near intersection of Tenahatchipi Pass detachment fault and the northwest-trending fault south of the Socorro Mine. Contacts with more intact rock bodies are faults.

**Tc**

1. **Arkosic sandstone and conglomerate** (Miocene or Oligocene) — Buff, moderately indurated arkosic sandstone. Clasts in conglomerate beds include rounded granitoid, subrounded dark gray andesite, lilac rhyodacite similar to unit Tv, buff-green feldspathic sandstone (similar to McCoy Mountains Formation). Medium scale cross-bedding is abundant. Sandstone is quartz-feldspar arenite. Isolated outcrops of this unit are overlain by alluvium (Qs), obscuring contacts with other Tertiary units.

2. **Conglomerate** (Miocene or Oligocene) — Red-brown cobble conglomerate. Clast types include schistose metamorphic rocks, abundant quartz-feldspathic mylonite, brick-red welded tuff (unit Tv?), and rare carbonate clasts. Igneous and metamorphic clasts are chloritically altered. Caliche horizons parallel to bedding may be old soils. One tuffaceous sandstone bed was observed. Conglomerate depositionally overlies volcanic rocks (Tv) south of Tenahatchipi Pass.

   A small outcrop of conglomerate south of the Hidden Treasure Mine is included in this unit. This conglomerate depositionally overlies chloritized mylonitic granodiorite, and consists of angular clasts of the underlying granodiorite in a red-brown sandy clay matrix, with rare clasts of Paleozoic rocks. Clasts are well imbricated.

**Tv** Felsic volcanic rocks (Miocene) — Interbedded ash flow tuff and tuffaceous sandstone. Red-brown rhyolite(?) with aphanitic mottled groundmass containing 1-2 mm rounded quartz and sanidine phenocrysts and 1 mm biotite phenocrysts; one flow grades up into lilac-gray welded tuff with well developed eutaxitic texture defined by flattened pumice pads and cognate inclusions. A thin section of rhyolite from south of the Hidden Treasure Mine took K-stain over its entire surface. This and the red-brown color suggests that the rhyolite is potassium-metasomatized. Interbedded sandstone is white to light greenish-gray, fine to medium-grained tuffaceous sandstone. Bedding is defined by grain size variations; beds are planar. Two flows and two sandstone units are present in outcrops south of Socorro Reef. Overlain depositionally by Tc south of Tenahatchipi Pass, otherwise contacts are faults.

**Tmd** Mafic dike (Miocene or Oligocene) — Dark gray-green, aphanitic to fine-grained, diorite to gabbro dikes. Fresh dike rock consists of hornblende and plagioclase, with an ophitic to intersertal texture. Grain size depends on dike thickness. Aphanitic chilled margins are generally 2-5 cm thick, dikes
more than 1.5 to 2 m thick have a fine-grained core, and 3-5 m thick dikes have a medium-fine-grained core. Most dikes are less than 2 m thick. Dikes generally trend east-west or northwest. Some dikes are associated with hematite and sparse copper-oxide mineralization along their margins. The associated alteration assemblage is generally sericite-chlorite-pyrite-earthy hematite (commonly after pyrite). One dike in the wash draining the south side of Tenahatchipi Pass contains inclusions of coarse-grained biotite hornblende up to 2 m in diameter. These dikes intrude all pre-Tertiary rocks.

**Ta** Andesite dike (Miocene or Oligocene)—2-10 m thick, light gray dike of very fine- to fine-grained, homogranular andesite, consisting of plagioclase, biotite, hornblende and minor quartz. Thickness, lateral continuity and intermediate composition contrast with dikes of Tmd swarm, but similar orientation suggests this dike may be related.

**TJm** Biotite porphyry (Tertiary or Jurassic) — Gray, 1-4 m thick dikes containing distinctive 2-5 mm diameter biotite phenocrysts in a very fine-grained to aphanitic groundmass. One thin section was examined. Biotite phenocrysts are altered to chlorite and opaque grains, with some tiny apatite grains along the cleavage planes. The groundmass consists of plagioclase lathes with about 5% acicular amphibole (hornblende?), and tiny disseminated opaque grains. Sparse augite (?) glomerocrysts up to about 5 mm diameter are altered to calcite. A series of dikes intrude Supai Formation in the Silver Queen Mine area. The dikes are aligned along a zone sub-parallel to layering in Supai Formation tectonite; the segments may be parts of a single dike broken by numerous small faults.

**JKg** Granodiorite (Cretaceous or Jurassic) — Fine-grained dark gray equigranular to slightly porphyritic granodiorite, consists of sparse K-feldspar in 1-2 cm elongate phenocrysts and plagioclase in 3-4 mm subhedral phenocrysts in a groundmass of quartz, plagioclase, and very fine-grained biotite. Intrudes granitoid of Socorro Suite, but contains inclusions of Bolsa and Coconino Quartzite and Supai Formation.

**Jv** Felsic volcanic rocks (Jurassic) — Locally flow banded maroon and purple dacite or rhyodacite lava (?) flows, agglomerates, and laminated and massive tuff; red, volcanic-lithic sandstones are interbedded in the southwest. Rhyodacite consists of an aphanitic groundmass with 1-2 mm diameter quartz and feldspar phenocrysts. Volcanic-lithic sandstones locally contain magnetite laminations in troughy cross-beds. White tuff (?) clasts are characteristic of sandstone in this unit; these are generally altered to very-fine grained white mica-quartz-feldspar aggregates and flattened in the incipient cleavage plane. Sandstone consists of 20-50% quartz in sub-angular to rounded grains. In thin section these include both clear volcanic (?) quartz and polycrystalline quartz from an igneous or metamorphic source. Clasts in conglomeratic beds include rounded vitreous quartzite (not from Paleozoic section), quartz porphyry (Jv ?), and other crystal poor volcanic rock fragments.

Unit crops out as isolated inselbergs south of Kaibab outcrops; based on relationships in Little Harquahala Mountains (Spencer and others, 1985), interpreted to overlie basal Mesozoic sediment unit (JTs) disconformably.

**Jqp** Quartz-feldspar porphyry (Jurassic) — Light gray quartz-feldspar porphyry dikes. Dikes are typically moderately to strongly cleaved and altered, consisting of a very fine-grained groundmass of sericite, chlorite, and quartz or feldspar. Phenocrysts form 10-20% of rock, and include 2-7 mm diameter quartz and 2-10 mm long K-feldspar (?). Quartz phenocrysts are ubiquitous, feldspar crystals are only locally present. Feldspar crystals commonly fractured normal to cleavage. Generally concordant with tectonite layering or bedding in Paleozoic strata. Dikes intrude Paleozoic strata, most commonly in Supai Formation.

**JYd** Mafic to intermediate intrusive rocks (Jurassic or Middle Proterozoic) — Mostly medium-fine grained, texturally variable diorite, locally ranges from gabbro (?) to granodiorite. Small pods disseminated in biotite granitoids, augen gneiss and Tenahatchipi gneiss are texturally variable metadiorite to metagabbro; these are medium- to medium fine-grained and consist of plagioclase, biotite, and hornblende altered to chlorite, biotite and epidote, locally with minor quartz. Nonfoliated to weakly foli-
ated. Diorite-gabbro bodies are typically injected by abundant aplite to pegmatite veins from 2 mm to 20 cm thick. Ophitic to sub-ophitic igneous texture is commonly preserved.

Dikes of fine-grained diorite that intrude gneisses in the Harquahala Plate are also included in this unit. These are typically moderately to strongly cleaved, and consist of very fine-grained, phyllitic chlorite, white mica, and feldspar, with sparse dark chlorite clots that may have been phenocrysts. These may be outlying diorite bodies related to the Jurassic Sore Fingers monzodiorite of the Hercules Plate [Isachsen et al., 1999], or may be related to Proterozoic magmatism.

**Granitic rocks (Jurassic or Early Proterozoic)** — Includes several separate small bodies of generally fine- to medium-grained equigranular biotite granodiorite. In the White Marble Mine area, foliated to non-foliated granodiorite forms irregular bodies 5-10 m long in marble of the Martin Formation. The granodiorite is medium grained, with euhedral to subhedral plagioclase and quartz, both 2-4 mm in diameter, in a groundmass of recrystallized fine-grained biotite, epidote, plagioclase, and quartz. Sparse blocky K-feldspar (?) phenocrysts are present. In the field, the contact between the granodiorite and Martin Formation was interpreted as a deformed intrusive contact. The contact is interdigitated, and deformation is heterogeneous. Apparently less deformed sections of the marble-granite contact (at a high angle to the foliation, in lenses of relatively weakly foliated rock) are sharp and tight, but irregular. Globs of actinolite-talc-carbonate hornfels are present along the contact. Superimposed fracturing and chloritization obscure the relationships. The Martin Formation is metasomatized to a talc-tremolite-carbonate hornfels in the area, and is unusually white. U-Pb isotopic analysis from a single zircon fraction extracted from this rock (Isachsen et al., 1999) yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ apparent age of 1324 Ma, and a $^{206}\text{Pb}/^{238}\text{U}$ apparent age of 590 Ma. These data suggest that the intrusive age may be Precambrian, and the discordance due to lead loss during deformation in the Harquahala Thrust shear zone. If the rock is Precambrian, then the granodiorite must have been mixed in the Martin Formation by shear-related processes, contrary to the apparent nature of the contacts in the field. Alternatively, the granodiorite may be Mesozoic with inherited radiogenic lead in the zircon. This second alternative is considered more likely based on the field relationships.

The granodiorite south of Hidden Treasure Mine is mylonitic and medium-grained. It contains 3-5 mm-diameter quartz grains, 5-10 mm-diameter pink K-feldspar, and 1-3 mm-diameter plagioclase in a dark green-gray, fine-grained groundmass of chlorite, epidote, quartz and feldspar. Mylonitic fabric is folded by kink bands and box folds with 0.5 to 1 m amplitude. This granodiorite is faulted against Paleozoic strata, and overlain depositionally by Tertiary conglomerate (Tc).

**Basal Mesozoic sedimentary rocks (Jurassic or Triassic)** — This unit is characterized by medium- to coarse-grained feldspathic sandstone and pebble to cobble conglomerate with siltstone partings. White mica (some possible detrital muscovite) is common. Color ranges from light gray to red brown or green-gray. Conglomerates are clast-supported or sand-dominated; clasts consist mostly of vitreous quartzite clasts of unknown derivation, but also include recognizable Paleozoic quartzite, chert and limestone. Except for the small exposure near the SW end of the Kaibab Limestone outcrop belt, rocks included in this unit are strongly cleaved and bedding is probably transposed. The basal contact is exposed in only one relatively undisrupted place, in NE, NE sec. 36, T. 5 N., R. 12 W., Socorro Mine 7.5' quadrangle. Tan, calcite-cemented quartz sand-stone interbedded with limestone at the top of the Permian Kaibab limestone is abruptly overlain by non-resistant, greenish-gray, chloritic quartz- and chert-elast sandstone, siltstone, and conglomerate. Unit adjacent to Kaibab Limestone tectonite, beneath Harquahala thrust on the hill S. of the Hidden Treasure mine is a red, calcareous fine-grained sandstone

**Kaibab Limestone (Permian)**

Strata correlated with Kaibab Limestone in the Harquahala Mountains can be divided into 5 mappable units throughout the Socorro Mine-White Marble mine outcrop area. The formation consists of limestone, cherty limestone, dolomite, and some sandstone. Crinoid columnals, productid brachiopods, and echinoid spines are common in several parts of the formation.
Evaporite member — Massive anhydrite or gypsum, very poorly exposed at surface. In mine tunnel and mine dump rock is massive white anhydrite or gypsum with some interlaminated siltstone. Waste rock from gypsum mine includes very light purple gray and green-gray mottled, quartz-rich, very fine-grained sandstone not exposed in outcrop. Contacts with other members of Kaibab not exposed. The stratigraphic position of the evaporite unit relative to unit 4 is unclear; the evaporite is only exposed in a structurally complex domain between transposed and non-transposed, overturned strata of unit 4. The absence of evaporitic rocks between the basal Mesozoic sandstone (Ps) and Kaibab Unit 4 on the hill south of the gypsum mine suggests that the gypsum is within Unit 4.

Unit 4 — Thick-bedded light gray, cherty and fossiliferous limestone, with locally preserved tan silty sandstone in upper part. Fossils include Chaetetes corals and brachiopods. Evaporite zone mapped as separate unit near gypsum mine on southwest side of the mouth of Hidden Treasure Canyon is probably interbedded within this unit.

Unit 3 — Medium-bedded dark-gray limestone, contains sparse, poorly preserved fusulinids and large gastropods.

Unit 2 — Massive, cherty, medium gray limestone. Rock is crinoid grainstone. Large productid brachiopods are abundant in the upper part.

Unit 1 — Basal sandy dolomite grades up into cherty, fossiliferous dolomitic limestone, with large crinoid columnals, echinoid spines and brachiopods. Top of unit is tan, silty sandstone that generally forms a slope or saddle. This member may correlate with the Toroweap Formation. Unit 1 becomes sandy at base, grading into Coconino Quartzite; dolomitic sandstone forms prominent black marker bed 2-4 m thick because it develops much darker desert varnish than underlying orthoquartzite or overlying dolomite.

Coconino Quartzite (Permian) — White, vitreous, fine- to medium-grained, well sorted quartzite; mostly very thin-bedded, plane laminated. Medium- to large-scale trough cross beds are present, but rarely visible. Thin green-gray shaly partings are locally present. Quartzite is highly fractured in general, and tends to form slopes and saddles. Very thin bedding is persistent even in highly deformed parts of unit in the northeast part of map area. Unit is 190 m thick. The contact on Supai Formation is placed at the base of non-calcareous quartzite. The top of this unit is the base of dark-brown weathering dolomitic sandstone at the base of Kaibab Limestone Unit 1.

Supai Formation (Pennsylvanian or Permian) — Interbedded, thick-bedded, white, vitreous quartzite, calcareous sandstone, maroon mudstone, limestone and dolomite. Beds are lenticular. This unit forms prominently banded, dark-brown desert-varnished outcrops. The base of the unit consists of about 15 m of dark gray shale and siltstone with thin, lenticular, red-chert-pebble conglomerate beds. In the northeastern part of the map area where metamorphic grade increases slightly, this basal shale forms a silvery-lilac calcareous phyllite. The interbedded character of the unit is preserved in the northeastern part of the map area where the unit is transposed, and consists of interleaved calc-silicate granofels and phyllite with white quartzite boudins. Basal contact is placed at the boundary between sandstone and mudstone (commonly phyllite) of the basal Supai and massive limestone (commonly with some terra rossa) of upper Redwall. This karst surface is irregular in detail but planar at map scale.

Redwall Limestone (Mississippian) — Lower thick-bedded light gray and orange limestone and dark gray dolomite form prominent ledges; overlain by variably dolomitized massive, cherty, light gray limestone; non-resistant crinoid grainstone is locally preserved beneath the karst zone at the top of the unit. This karst zone is 5-20 m thick and consists of irregular limestone gobs 5 to 30 cm in diameter in a matrix of maroon to purple gray phyllite. A thin karst breccia, 1-2 m thick, is locally present at the base. In the White Marble Mine area, white dolomite of the Martin Formation is difficult to distinguish from the lower dolomite of the Redwall, and the contact is placed where the marble
becomes cherty. This contact probably is not in the same stratigraphic position as the contact mapped in less metamorphosed areas to the southwest. The Redwall Limestone (marble) in the White Marble Mine area contains much more chert than in other parts of the map area, and was thought for a time to be Kaibab Limestone unit 2. Interpretation as anomalous Redwall Limestone is preferred in view of the absence of a mappable fault that would separate Martin and Kaibab in this area, and the absence of other members of the Kaibab in association with the cherty marble. The Redwall is about 100 m thick. The basal contact is placed at the base of an orange and white varicolored crystalline limestone bed 2-4 m thick that separates massive gray Redwall dolomite from the medium-bedded, tan-gray dolomite of the Martin Formation.

**Dm** Martin Formation (Late Devonian) — Brown, gray and tan dolomite and dolomitic limestone; chocolate brown sandy dolomite at the base; one or two coarse, poorly-sorted sandstone beds are present; carbonate beds are laminated, massive and mottled. Metamorphosed Martin is a white, talc-tremolite-dolomite-quartz marble. On the klappe southwest of the White Marble Mine (Hat Mountain) the Martin is locally metasomatized to a tremolite granofels along steep, northwest-trending fractures. The unit is about 100 m thick. Base of unit is 1-2 m thick chocolate brown weathering, siliceous dolomite that typically forms a prominent ledge at the top of a slope on Abrigo Formation shale or phyllite. This unit is not recognizable in the White Marble mine area because of metamorphism.

**Ca** Abrigo Formation (Late Cambrian and Middle Cambrian) — Dark gray, maroon and gray-green sandy shale interbedded with very thin fine-grained feldspathic sandstone. Some thin siltstone beds are bioturbated. Unit is up to 27 m thick. Internal faulting and folding makes thickness determination approximate. Basal contact on Bolsa Quartzite is gradational. Upper contact with Martin Formation is sharp.

**Cb** Bolsa Quartzite (Middle Cambrian) — Maroon-gray feldspathic sandstone; grit and pebble conglomerate at the base are overlain by medium- to fine-grained sandstone with siltstone partings up section. Planar tabular cross beds are common. Uppermost part is gradational into Abrigo Formation as beds become thinner, finer grained, and have more interbedded shale. Basal non-conformity on Proterozoic granitoid is a nearly planar surface. The exact contact is sometimes hard to locate because of the similarity between granite in the paleo-weathered zone at the contact and the coarse arkose at the base of the Bolsa. A few bull quartz pebbles or cobbles are present in the basal Bolsa in some areas.

**Yg** Granitic rocks (Middle Proterozoic) — Equigranular to slightly porphyritic granitoid in the White Marble Mine area that somewhat resembles the biotite monzogranite of the Socorro suite, non-porphyritic Harquahala granite and other biotite monzogranite exposed off the map sheet (Blue Tank Granite [Richard, 1988]) to the southeast in the Harquahala Plate. Correlation of this unit is uncertain. The contact with Harquahala Granite (Yh) in the strongly deformed granite sheet beneath the Harquahala thrust is gradational, but the nature of the contact is obscured by deformation. Other outcrops of the unit are fault-bounded.

**Socorro suite (Middle Proterozoic)**

The Socorro suite forms a zoned plutonic complex that underlies Paleozoic rocks of the Centennial Plate in the Western Harquahala Mountains. The most abundant rock type is coarse-grained, slightly porphyrytic granite, the Socorro Granite [Varga, 1977]; this grades into a finer grained, more distinctly porphyrytic biotite granite. Equigranular to slightly porphyrytic muscovite granite forms a north-trending core zone of the complex. These rocks are continuous beyond the map area into the Little Harquahala Mountains, but the phases were not mapped separately by Spencer et al. [1985]. Subsequent reconnaissance indicates that the muscovite granite phase is present in the northeastern Little Harquahala Mountains, but the coarse-grained phase in dominant in other parts of the Centennial plate in that range.
Socorro granite — Generally coarse-grained porphyritic granitoid consisting of 20-30% quartz and plagioclase in grains up to 1 cm in diameter, potassium feldspar in blocky, equant phenocrysts that are 2-3 cm in diameter, and 2-4% biotite in 1-2 mm flakes and very fine-grained aggregates. Rock is locally equigranular. Differs from the porphyritic granitoid of Socorro Suite because it is generally coarser-grained, contains more quartz, the phenocrysts are more equant, and the grain size difference between the phenocrysts and groundmass is not as great. The contact with porphyritic granitoid of the Socorro Suite (Ysb) is gradational.

Muscovite granite — Medium-grained (3-5 mm diameter) monzogranite in western Harquahala Mountains; consists of 20-30% anhedral quartz, plagioclase, K-feldspar, 1-4% biotite in very fine-grained aggregates, and up to 4% muscovite in 0.5-3 mm diameter flakes. Homogranular in general, but grades into porphyritic phases with elongate K-feldspar phenocrysts up to 3 cm long. Rock near margins of pluton is texturally variable fine- to medium-fine-grained aplitic granite with 1-2% biotite. Dikes of muscovite granite intrude porphyritic biotite granite of Socorro Suite (Ysb) near the contact north of Socorro Peak. Inclusions of Ysb are present in the aplitic border zone north of the map area.

Biotite granitoid — The porphyritic biotite monzogranite is medium coarse-grained, and consists of 15-25% rounded, equant or anhedral quartz in grains up to 7 mm in diameter, K-feldspar in elongate ('boxcar') phenocrysts up to 3 cm long, anhedral plagioclase 1-4 mm in diameter, 5% biotite in very fine-grained clots up to 2 mm in diameter and locally as 1-2 mm flakes, and accessory magnetite. Generally medium to dark gray even when altered. Locally grades to quartz-feldspar porphyry or medium-grained equigranular phase. A zone of medium fine-grained equigranular leucogranite is present near the margins of the body in some areas. The leucogranite in this border zone contains rounded quartz phenocrysts 2-4 mm in diameter. Granite mapped as Ygu at the north base of Hat Mountain is more equigranular than this granite. The biotite granitoid appears to intrude Socorro granite in Tenahatchipi Pass. The contact with Socorro granite on the west side of Socorro Peak is gradational and is abundantly intruded by aplitic leucogranite dikes and stocks.

Harquahala Granite (Middle Proterozoic) — Megacrystic biotite granodiorite to granite containing 20-35% equant, blocky K-feldspar phenocrysts up to 5 cm in diameter. Plagioclase is recrystallized to fine-grained aggregates of oligoclase or albite, white mica, and epidote. Biotite (3-7%) and muscovite (1-2%) occur as fine-grained aggregates and disseminated grains; most of the muscovite is probably the product of metamorphic reactions involving biotite and the feldspars. Sparse but ubiquitous accessory sphene and allanite occur in 1 to 3 mm euhedral or anhedral grains. A medium- to fine-grained equigranular to slightly porphyritic granodiorite border(?) phase contains 15% quartz in 1-5 mm grains, 7% biotite in very fine-grained aggregates, plagioclase in 2-4 mm grains, and sparse K-feldspar in elongate 1-3 cm phenocrysts. The relationship of Harquahala granite to Socorro granite is obscured by alteration, and the two granite bodies may be phases of the same pluton. Harquahala granite generally contains more biotite and less quartz than Socorro, and its texture is more distinctly porphyritic. Harquahala Granite is overlain depositionally by Bolsa Quartzite.

Fine-grained granite (Middle Proterozoic) — Consists of subequal amounts of anhedral microcline, plagioclase, and quartz, and 2-4% biotite. Similar granites in nearby areas locally contain 1-3% muscovite. Rock is homogrannular with 1-3 mm grain size and aplitic texture. Plagioclase is mostly untwinned and difficult to distinguish from quartz. The fine-grained granite intrudes the Harquahala granite as dikes, locally grading to homogeneous bodies through irregular mixed zones. Xenoliths of Harquahala Granite have been observed in this fine-grained granite in nearby areas. Similarity of trace-element chemistry and spatial association suggests that this fine-grained granite is related to the Harquahala granite (S.M. Richard and Ed DeWitt, unpublished data, 1987).

Fine-grained granodioritic rocks (Middle Proterozoic or Early Proterozoic) — Mixed unit that includes fine-grained, foliated granodiorite, nonfoliated granodiorite to monzogranite resembling the Jurassic or Cretaceous fine-grained granodiorite (unit JKgd), and hypidiomorphic-granular granodior-
ite to monzogranite that grades into Harquahala granite and is probably a border phase. Contacts between these phases appear gradational, and were not mapped. The foliated granodiorite is commonly spotted with 30-40% of 1-2 cm diameter elliptical, fine-grained, quartz-K feldspar aggregates in a groundmass of fine-grained plagioclase, biotite and quartz, with abundant accessory sphene. Foliation is defined by flattening of spots and biotite-rich laminations. The contact between the foliated phase and biotite granitoids of the Socorro suite is gradational. Nonfoliated medium fine-grained, hypidiomorphic granular monzogranite phase contains 20% 5-7 mm K-feldspar, 25-35% 1-2 mm plagioclase, 40% anhedral quartz, 5-7% biotite, with accessory magnetite and sphene is associated with the Harquahala granite and may be a border phase. Nonfoliated granodiorite phase, resembling unit JKg, is dark gray and consists of 15-20% quartz, 70-80% plagioclase, and 5-7% biotite forming a fine-grained equigranular matrix with sparse small quartz phenocrysts and elongate K-feldspar phenocrysts up to 2 cm long. Contains inclusions of Y's and Ygc(?).

Xlg  Hyduke leucogranite and pegmatite (Early Proterozoic) — Medium fine- to fine-grained, equigranular muscovite leucogranite. Although the modal mineralogy of these granitoids makes them granodiorite, the petrographic texture of the feldspar suggests that much of the feldspar is albite-zoned K-feldspar. Primary plagioclase occurs in anhedral, twinned grains and is albite or oligoclase. Altered K-feldspar(?) forms very fine-grained aggregates of untwinned plagioclase (albite?), white mica, epidote and quartz. Relict K-feldspar is commonly in crystallographic continuity with adjacent plagioclase. If these aggregates were originally K-feldspar grains, the rock would have been a monzogranite. Muscovite ranges in abundance from about 2% to 10%, and occurs as 1 to 2 mm flakes. Abundant pegmatite is associated with the leucogranite. Pegmatites consist of quartz, albite, muscovite, and microcline; they intrude as irregular, unzoned sills and dikes. Muscovite leucogranite intrudes the mafic and heterogeneous gneiss units (Xm and Xgn). Contacts are generally sharp, but some mixing of granite and gneiss is common. Named for exposures around Hyduke Mine in central Harquahala Mountains [Richard, 1988].

Xag  Augen gneiss (Early Proterozoic) — Dark gray-weathering augen gneiss containing 2-3 cm diameter, rounded K-feldspar augen with irregular, corroded margins. Augen are commonly fractured with quartz filling, or have quartz and feldspar inclusions. The groundmass is an aggregate of granular quartz and feldspar with disseminated very fine-grained biotite. About 15-25% of rock is quartz, mostly in 1-3 mm granular aggregates and anhedral grains in a mat of sericitized plagioclase, chloritized biotite and microgranular epidote. Some quartz aggregates are up to 7 mm in diameter. Plagioclase is moderately to strongly sericitized. Medium- to fine-grained leucogranite dikes and concordant pods and lenses of medium-grained diorite or gabbro (Yd?) are common. Strongly resembles foliated Socorro granite (Y sb), but contains less quartz and more biotite. Augen gneiss is interleaved with Tenahatchipi gneiss at their contact.

Xgn  Heterogeneous gneiss (Early Proterozoic) — Quartz-feldspar-biotite gneiss characterizes this unit, which is otherwise notable only for its variability. Rock types include pelitic schist, actinolite hornblende-feldspar-quartz gneiss, biotite-epidote-amphibole-rich gneiss, and rare quartz-magnetite granofels. Foliation defined by mineralogical and textural variations is generally regular and planar. Retrograde(? chlorite is common. Small, irregular bodies of medium-grained biotite granitoid are present. Mineral assemblages indicate upper greenschist to lower amphibolite facies metamorphism. The contact with mafic gneiss unit is only approximately located and the nature of this contact is uncertain.

Xm  Mafic gneiss (Early Proterozoic) — Compositionally banded hornblende-rich gneisses ranging from amphibolite to plagioclase-biotite-hornblende gneiss. The typical gneiss is fine-grained and equigranular, with 2-15 cm thick bands defined by plagioclase-rich and plagioclase-poor layers. The foliation is generally quite regular.

Xt  Tenahatchipi Gneiss (Early Proterozoic) — Heterogeneous, fine-grained migmatitic gneiss. Paleosome is amphibolite to biotite-hornblende-feldspar-quartz and quartzo-feldspathic gneiss. Mafic to intermedi-
ate composition paleosome is fine-grained and occurs as concordant rafts in the foliation. Fine-grained quartz-feldspar-muscovite-biotite gneiss is the most abundant paleosome; foliation is 2-20 cm banding defined by mineralogical and textural variations, especially biotite concentrations. This is abundantly injected by leucogranite neosome that occurs as everything from concordant, foliated layers in the gneiss to cross-cutting, unfoliated injections. Tenahatchipi Gneiss and augen gneiss (Xag) are interleaved over 10-20 m at their contact. A Jurassic $^{40}$Ar/$^{39}$Ar plateau age from hornblende in probably correlative gneiss in the Little Harquahala Mountains [Richard et al., 1998], and preliminary U-Pb data from a leucocratic granite dike in the gneiss [R. M. Tosdal, personal communication, 1997] suggests the possibility that the Tenahatchipi Gneiss may have experienced a Jurassic metamorphism.

REFERENCES


